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REVISIONS TO THE TECHNICAL REPORT ON SPACE DEBRIS OF THE SCIENTIFIC AND TECHNICAL SUBCOMMITTEE **

(Revisions indicated in **BOLD**)

1. Measurements of space debris

1.1 *Ground-based measurements*

1.1.1 *Radar measurements*

1. Ground-based radars are well suited to observe space objects because of their all-weather and day-and-night performance. The radar power budget **and operating wave length are** limiting factor**s** for detection of small objects at long ranges.

2. Basically two types of radars are used for space object measurements:

(a) Radars with mechanically controlled beam direction using parabolic reflector antennas. Only objects being in the actual field-of-view - given by the mechanical direction of the parabolic reflector antenna - can be detected and measured;

(b) Radars with electronically controlled beam direction using phased array antennas. Hundreds of objects at different directions can be detected and measured simultaneously.

3. The first type of radar is used mainly for tracking, and the second for **both tracking and** search tasks.

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* This document has not been edited.

** The original technical report on Space Debris of the Scientific and Technical Subcommittee is contained in document A/AC.105/637 paras. 94-137.

4. The following radar modes are used for observation of space debris: tracking mode; beam-park mode; mixed mode; and bistatic mode.

5. In the tracking mode the radar follows an object for a few minutes, gaining data on angular direction, range, range-rate, amplitude and phase of the radar echoes. From the evaluation of direction, speed and range-rate as a function of time, orbital elements can be derived.

6. In the beam-park mode, the antenna is kept fixed in a given direction and echoes are received from objects passing within its field-of-view. This gives statistical information on the number and size of the detected objects, but less precise data on their orbit.

7. In the mixed mode, the radar would start in the beam-park mode and change to the tracking mode when an object passes the beam, thereby gaining more precise orbital data. Once the data are collected, the radar might return to the beam-park mode.

8. In the bistatic mode, an additional receiver antenna, separate from the emitting antenna, is used. This allows a greater sensitivity in the bistatic antenna, which is then able to detect smaller objects.

9. From radar measurements principally, the following space object characteristics can be derived**. All of the following parameters will have some degree of uncertainty:**

(a) Orbital elements describing the motion of the object's centre of mass around the Earth;

(b) Attitude describing the motion of the object around its centre of mass;

(c) Size and shape of the object;

(d) Orbital lifetime;

(e) Ballistic coefficient, as defined in paragraph 127 (f), specifying the rate at which the orbital semi-major axis decays;

(f) Object mass;

(g) Material properties.

10. The deterministic data can go into a catalogue of space objects, as well as the statistical information on numbers of detected objects of a given size in a given region at a certain time.

11. Current radars are able to detect objects larger than 1 centimetre up to a range of 1,000 kilometres or 1 metre in geostationary orbit (**GEO**). In order to detect smaller objects, the bistatic radar mode **may** be adopted. Using this technique, 2-millimetre-sized objects can be detected at ranges of 500 kilometres. These detection ranges apply to highly reflective objects like metals. For other materials, like composites, the reflection of radar signals **may be** weaker.

12. Radar measurements of orbital debris population statistics at sizes **smaller than 30** centimetres (the nominal limit for the United States and Russian Federation catalogues) have been conducted by the United States using Haystack and Goldstone radars, **some Russian radars,** and by Germany, using the FGAN radar

and the Effelsberg Radio Telescope. Haystack and Goldstone radars have provided a statistical picture of the low Earth orbit (LEO) debris environment at sizes down to 0.5 centimetre (with some data down to 0.2 centimetre**)**. FGAN radar measurements have not extended to quite such small sizes, but in general agree with the NASA results. The picture that emerges from these **and other** measurements is that the debris population exceeds the natural meteoroid population for all sizes larger than about 0.01 centimetre in diameter.

13. The MU radar of Kyoto University of Japan can observe the radar cross-section (RCS) variation of unknown objects for a period of 20 seconds. A bistatic radar system of the Institute of Space and Astronomical Sciences (ISAS) of Japan can detect objects as small as 2 cm at an altitude of 500 kilometres.

1.1.2 *Optical measurements*

14. Optical debris can be detected by reflected sunlight when the debris object is sunlit while the ground below is dark. For objects in LEO, this period is limited to an hour or two just after sunset or before sunrise. However, for objects in high Earth orbit (HEO), such as those in geosynchronous orbit, observations can often be continued during the entire night. The requirement for clear, dark skies is another limitation on optical measurements. An advantage of optical measurements over radar measurements is that the signal intensity from reflected sunlight falls off only as the square of the distance or altitude, whereas the radar signal return falls off as the fourth power of distance. The result is that a telescope of modest size can outperform most radars for detection of debris at extreme altitudes. Some measurement of small debris in LEO have been done using optical telescopes, but in general, radars outperform telescopes for measurements in LEO.

15. The United States Space Command employs 1-metre aperture telescopes fitted with intensified vidicon detectors to track HEO objects. These measurements are used to maintain the HEO part of the Space Command catalogue. The capability of these telescopes is limited to detection of 1-metre objects at geosynchronous altitudes, corresponding to a limiting stellar magnitude of 16. Charge-coupled device (CCD) detectors are planned for these telescopes, which will improve their performance. The Russian Space Agency has a similar telescope capability used to maintain the orbits of HEO objects in their catalogue.

16. In general, the United States Space Command and the Russian Federation **GEO** catalogues are concerned with intact spacecraft and rocket bodies. However, there are reasons to believe that small orbital debris resulting from explosions also exist in the **GEO** region. A Russian Federation Ekran satellite in **GEO** was observed to explode in 1978. **M**any uncatalogued objects **have been** seen in high elliptical orbits at an inclination of 7 degrees, possibly the result of Ariane geotransfer stage breakup**s**. The United States Space Command telescope on Maui, Hawaii accidentally observed the breakup of a Titan transtage (1968-081E) in February 1992. There are other **stages** near **GEO** that may still have the potential to explode. Some of these stages appear to be lost, and may have exploded.

17. An exceptional combination of sensitivity and field of view is required to survey the **GEO** region for the small orbital debris that are suspected to exist there. A limiting stellar magnitude of 17 or greater is needed to detect debris smaller than 1 metre near geosynchronous altitude, and as wide a field-of-view as possible is needed to allow rapid survey of large areas. Most astronomical telescopes that have sufficient sensitivity have a small field-of-view. This is useful for accurate determination of satellite positions (once their approximate locations are known), but not for surveying large areas of the sky.

18. Some preliminary measurements have been done to survey the region near **GEO** for debris objects smaller than 1 metre. NASA used a small telescope capable of detecting objects as faint as 17.1 stellar

magnitude (equivalent to an object of about 0.6 metre in diameter at geosynchronous altitude), with a field-of-view of about 1.5 degrees. The results showed that there does exist an appreciable population of debris near these altitudes. Further debris surveys are justified. **The IADC is presently discussing plans for an exploratory GEO orbital debris campaign.**

19. The existing and planned optical capabilities for optical observation of debris are summarized in table 1 below:

Table 1. Optical facilities for debris observation
(To be completed)

Country/ Organization	Organization	Telescope aperture (metres)	Field-of-view (degrees)	Detection type	Limiting magnitude	Status
Japan	SUNDAI	0.75	0.04	CCD	17.0	Operational
Japan	CRL	1.5	0.28	CCD		Operational
ESA	ESA	1.0	1.0	CCD	19.0	Development
Russian Federation	RAC	1.0		CCD	20.0	Operational
Russian Federation	RSA	0.6	0.2	TV	19.0	Operational
Switzerland	University of Bern	1.0		CCD		Development
United States	NASA	0.3	1.5	CCD	17.1	Operational
United States	NASA	3.0	0.3	CCD	21.5	Operational
United Kingdom	Royal Greenwich Observatory	0.2	0.25	CCD		Operational

1.2 *Space-based measurements*

1.2.1 *Retrieved surfaces and impact detectors*

20. Information on submillimetre-size particles can be gained with the analysis, after return to Earth, of surfaces or spacecraft exposed to the space environment. Similar information can also be obtained through dedicated debris and dust detectors. **Most** of them contain, as a key element, a detection surface. Some of them are designed to catch an impact particle for further analysis. For cost reasons, surfaces are retrieved for later analysis only from LEO.

Examples **of retrieved spacecraft and surfaces** are given in table 2 below.

Table 2. Examples of retrieved spacecraft and surfaces
(To be completed)

Name	*Orbit*	*In orbit*	*Stabilization*	*Exposed area*
LDEF (NASA)	340-470 km 28.5 degrees	4/84-1/90	Gravity-gradient	151 square metres
EURECA (ESA)	520 km 28.5 degrees	7/92-6/93	Sun-pointing	35 square meters spacecraft + 96 square meters solar arrays
HST Solar Array (**ESA/NASA**)	610 km 28.5 degrees	5/90-12/93	Sun-pointing	62 squares metres
MIR/EUROMIR 95 (RSA/ESA)	390 km 51.6 degrees	10/95-2/96	Gravity-gradient	20 x 30 cm (cassette)
SFU (JAPAN)	300-500 km 28.5 degrees	3/95-1/96	Sun-pointing	**20** square metres
Space Shuttle (NASA) Orbiter	300-**600** km 28.5-**51.6** degrees	1992-present	various	100 square metres

21. After exposure to the space environment, spacecraft surfaces are covered with a large number of impacts of meteoroids and debris. The size of individual impact craters and holes extends from micrometres to several millimetres. A basic problem is to distinguish between impacts of meteoroids and man-made debris. A proven method to determine their origin is chemical analysis. However, there are some difficulties associated with this method. Because of the high impact speed, little of the impacting material survives unaltered. The particle vaporizes and then recondenses on the surrounding surfaces. In many cases the origin of an impacting particle cannot be uniquely determined (lack of residue or chemical analysis not conclusive). In order to relate the size of the impact feature with the size of the particle, ground-calibration tests (hypervelocity impact tests) have been performed for different materials.

22. From impact statistics and calibration experiments, the flux for meteoroids and debris can be determined as a function of particle size. An important issue to be considered is that of secondary impacts. If these are not properly treated, the derived flux figures will be overestimated.

23. LDEF was covered by more than 30,000 craters visible to the naked eye, of which 5,000 had a diameter larger than 0.5 millimetre. The largest crater of 5 millimetres in diameter was probably caused by a 1 millimetre particle. The LDEF showed that some impacts were clustered in time, and it also points to the existence of a submillimetre population in elliptical orbits.

24. On EURECA the largest impact crater diameter was 6.4 millimetres. Among the retrieved surfaces, the returned solar array of the Hubble Space Telescope (HST) had been the one with the highest orbit altitude. An interesting finding was that the impact flux for HST was considerably higher (factor 2-8) than for EURECA for crater pit sizes larger than 200-300 microns.

25. The Space Flyer Unit (SFU) launched in March 1995 was retrieved by the Space Shuttle in January 1996. A post-flight analysis (PFA) is **under-way**.

26. The cases discussed above give evidence of the effect of the particulate environment on spacecraft in orbit. In all cases no functional degradation of the spacecraft was observed. Available information on the submillimetre population is limited to altitudes below 600 kilometres. In particular, no information is available in the regions of highest density of space debris in LEO (at an altitude of about 800-1000 kilometres) as well as in the geostationary orbit. **In 1996**, a**n ESA** debris and dust detector **was placed** in the geostationary orbit **on the Russian spacecraft Express-2**.

1.2.2 ***Space-based debris*** *measurements*

27. Space-based measurements in general have the advantage of higher resolution because of the smaller distance between the observer and object. Also, there is no disturbing effect of the atmosphere (extinction and absorption of electromagnetic signals). Obviously, costs of space-based systems are in general higher than those on ground, and careful cost-performance trade-offs are needed.

28. The infrared astronomical satellite IRAS, launched in 1983 to perform a sky survey at wavelengths ranging from 8 to 120 micrometres, was operational during the 10 months in a sun synchronous orbit near an altitude of 900 kilometres. The satellite was pointing radially away from Earth and scanning the celestial sphere. The complete set of unprocessed IRAS data has been analysed by the Space Research Organization of the Netherlands (SRON), Groningen, in order to characterize the infrared emission of debris objects and to extract a comprehensive set of debris sightings. The method of identifying space debris signatures is based on the recognition of their track over the IRAS focal plane. The 200,000 potential debris sightings are stored in a database. About 10,000 sightings are attributed to real objects. From the debris sightings, it is not possible to compute the orbital elements of a debris object in a unique manner.

29. In 1996, the United States launched the MSX spacecraft into a 900 km orbit. Its visible and infrared sensors are being used to observe near-by small debris.

1.3 *Cataloguing and databases*

30. A catalogue is a record of the characteristics of the orbital population that have been derived from measurements or records. The purposes of a catalogue are to provide correlation with observations of orbiting objects; to act as a historical record of orbital activity for the purposes of environment monitoring; to serve as an input to modelling the behaviour of orbiting objects; and to provide a basis for predicting future launch and operational activity.

31. The following characteristics of orbiting objects **may be** recorded:

(a) Mass: the launch mass, beginning of life mass and dry mass (end of life);

(b) Radar cross-section: the returned signature of an orbiting object from which shape, orientation and size can be derived;

(c) Albedo: a measure of the reflectivity of an object which characterizes the optical visibility of an object;

(d) Dimensions;

(e) Orientation;

(f) Ballistic coefficient: a measure of the aerodynamic and mass-geometric characteristics of the object which will influence the orbital lifetime of an object until its entry into the upper atmosphere;

(g) Material construction: although not currently of importance, to effectively represent shedding of micro-debris would require the definition of surface characteristics;

(h) State vectors: the characteristics of the orbit of an object derived at a particular instant in time;

(i) Launch characteristics: this will include the launch vehicle, launch date and launch site.

32. There are two catalogues of space objects which are frequently updated by observations: the United States Space Command catalogue; and the Russian Federation space object catalogue. **Data** are **also** archived in the DISCOS database of ESA.

33. NASDA is studying a debris database **which can provide data to the** international **common** debris database **presently being** discussed **in the** IADC. **NASDA is also studying a trajectory prediction analysis for reentering objects and collision avoidance analysis for new launches.**

34. NASDA currently depends on the United States Space Command orbital element data as **the** source of **its** debris database. NASDA will add the orbital data of **its own spacecraft** acquired through **observations conducted by the National Astronomy Observatory.**

35. A catalogue record can be stored through a number of media. A hard copy (paper) format is not well suited to the dynamic nature of the orbital population. An electronic format is well suited to the recording of such information; modification and updating of characteristics; manipulation of data for the purposes of comparison and input to models; and access via networks by users for the purposes of interrogation and contribution.

1.4 *Effects of the space debris environment on the operation of space systems*

36. Four factors determine how the space debris environment affects space systems operations. These are time in orbit, projected area, orbital altitude and orbital inclination. Of these, time in orbit, projected area and orbital altitude are the dominant factors.

1.4.1 *Effects of large debris objects on the operation of space systems*

37. Large debris objects are typically defined as objects larger than 10 centimetres in size. Such objects are capable of being tracked, and orbital elements are maintained. During the course of shuttle missions, orbiters have execute**d** collision avoidance manoeuvres in order to avoid catastrophic collisions with these large debris objects. **In 1996, the first recorded natural collision occurred between two catalogued objects, the operational Cerise satellite and a fragment from an exploded Ariane upper stage.**

1.4.2 *Effects of small debris objects on the operation of space systems*

38. To date, small debris objects (smaller than a few millimetres in diameter) have caused damage to operational space systems. **These impacts have had no known effect on mission success.** This damage

can be divided into two categories. The first category is damage to surfaces or subsystems. The second category is the effect on operations.

1.4.2.1 *Damage to surface or subsystems*

39. Examples of damage that affect the surface of operational systems are:

(a) Damage to shuttle windows;

(b) Damage to the Hubble Space Telescope (HST) high gain antenna;

(c) Severing of the Small Expendable Deployer System - 2 (SEDS-2) tether;

(d) Damage to other exposed shuttle surfaces.

In (a), (b) and (d), there is clear evidence of damage due to orbital debris. In (c) , it is unclear whether this damage was caused by man-made debris or a micrometeroid.

1.4.2.2 *Effects of space debris on* ***human*** *space operations*

40. In order to protect crews from debris during flight, operational procedures have been adopted. In the case of the **S**pace **S**huttle, the **O**rbiter is **often** oriented during flight with the tail pointed in the direction of the velocity vector. This flight orientation was adopted to protect the crew and sensitive orbiter systems from damage caused by collisions with small debris.

41. Operational restrictions have also been adopted for extravehicular activities (EVAs). Whenever possible, EVAs are conducted in such a way as to ensure that the EVA crew is shielded from debris by the orbiter.

1.5 Other effects of space debris

42. Astronomers observe during wide field imaging an increasing number of trails per plate caused by orbital debris. These trails degrade the quality of the observation. Orbital debris trailing will entirely negate a photometric observation should debris cross the narrow photometric field.